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FOR

METHOD OF SIGNAL TRANSMISSION IN A WDM COMMUNICATION SYSTEM

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METHOD OF SIGNAL TRANSMISSION IN A WDM COMMUNICATION SYSTEM

BACKGROUND OF THE INVENTION

Field of the Invention

5   The present invention relates to optical communication equipment and, more specifically, to equipment for WDM communication systems.

Description of the Related Art

To achieve high transmission capacity, wavelength-division multiplexing (WDM)

10   communication systems should have relatively high spectral efficiency. For example, to achieve a capacity of 1.2 Tbit/s, a WDM system operating over a wavelength range of about 25 nm (3.1 THz) should have a spectral efficiency of about 0.4 bit/s/Hz. This corresponds to a channel spacing of about 0.8 nm (100 GHz) for a bit rate of 40 Gbit/s. With WDM channel packing this dense, narrow bandpass filtering should be employed to provide good channel isolation/crosstalk

15   reduction. However, this filtering also results in optical waveform distortion, which increases the number of decoding errors at the receiver. It is therefore desirable to have a method of signal transmission that would mitigate the effects of narrow bandpass filtering in dense WDM communication systems.

20   ## SUMMARY OF THE INVENTION

Problems in the prior art are addressed, in accordance with the principles of the present invention, by a method of signal transmission in a WDM communication system, according to which an optical transmitter is overdriven to produce a favorable phase shift between different optical bits. In a representative embodiment, a transmitter of a WDM communication system is

25   equipped with a Mach-Zehnder modulator (MZM) configured to produce an optical signal corresponding to a duobinary data stream by modulating a beam of light passing through the MZM. A three-level electrical signal is applied to the MZM to modulate the light. At the second signal level, the modulator substantially blocks light transmission. At the first and third levels, the modulator transmits light corresponding to the duobinary "–1" and "+1" bits, respectively, such

30   that a relative phase shift between the optical bits is different than 180 degrees, i.e., the phase shift value employed in prior-art optical duobinary modulation. Advantageously, by appropriately selecting voltages for the first and third levels, the relative phase shift between the optical bits can be adjusted to reduce detrimental effects of optical bandpass filtering typically present in the WDM communication system, thereby reducing the number of decoding errors at the receiver.

35   According to one embodiment, the present invention is a method of signal transmission in a communication system, comprising: (A) transmitting an optical beam through a modulator

adapted to: (1) have a peak of light transmission at a first voltage; (2) substantially block light transmission at a second voltage greater than the first voltage; and (3) have another peak of light transmission at a third voltage greater than the second voltage; and (B) driving the modulator with an electrical signal having two or more levels, wherein: (i) a first level is outside of a voltage range

5   between the first and third voltages; and (ii) a second level is either inside the voltage range between the first and third voltages or outside of said voltage range on the opposite side from the first level.

According to another embodiment, the present invention is a transmitter for a communication system, comprising: (A) a modulator configured to transmit light generated by a

10   light source, wherein the modulator is adapted to: (1) have a peak of light transmission at a first voltage; (2) substantially block light transmission at a second voltage greater than the first voltage; and (3) have another peak of light transmission at a third voltage greater than the second voltage; and (B) a driver configured to drive the modulator with an electrical signal having two or more levels, wherein: (i) a first level is outside of a voltage range between the first and third voltages;

15   and (ii) a second level is either inside the voltage range between the first and third voltages or outside of said voltage range on the opposite side from the first level.

According to yet another embodiment, the present invention is a communication system, comprising an optical transmitter and an optical receiver coupled via a communication link, wherein: (i) the optical transmitter comprises: a modulator adapted to modulate an optical beam

20   with data; and a driver adapted to drive the modulator with an electrical signal corresponding to the data; (ii) the communication link subjects the modulated beam to bandpass filtering; and (iii) the modulator is overdriven to introduce a phase shift between optical symbols in the modulated beam such that, at the receiver, inter-symbol interference caused by the bandpass filtering is reduced.

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BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and benefits of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which:

30   Fig. 1 shows a representative WDM communication system, in which the present invention may be practiced;

Fig. 2 shows another representative WDM communication system, in which the present invention may be practiced;

Fig. 3 shows a block diagram of an optical transmitter that can be used in the WDM

35   communication systems of Figs. 1 and 2;

Fig. 4 graphically illustrates operation of a Mach-Zehnder modulator (MZM) used in the optical transmitter of Fig. 3 according to certain embodiments of the present invention;

Figs. 5A-B graphically show performance of the system shown in Fig. 1, when it is operated to transmit duobinary optical signals according to a prior-art method and one embodiment of the present invention, respectively; and

Fig. 6 graphically demonstrates improvements in receiver sensitivity resulting from the use of one embodiment of the present invention.

DETAILED DESCRIPTION

Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments.

Fig. 1 shows a representative WDM communication system 100 in which the present invention may be practiced. System 100 has N optical transmitters 102-i (where i = 1, 2, ... N), each sending an optical signal corresponding to a WDM channel and operating at a designated wavelength. An optical multiplexer (MUX) 104 combines the outputs of transmitters 102-i into a multiplexed optical signal, which is then transmitted to optical de-multiplexer (De-MUX) 110 through spans of optical fiber 106 and optical bandpass filters 108 interposed between the optical multiplexer and de-multiplexer. Optical de-multiplexer 110 decomposes the received multiplexed signal into its individual wavelength components, each of which is then applied to and processed by a corresponding optical receiver 112-i. In one implementation, WDM channel spacing in system 100 is less than about 1 nm and filters 108 are configured to provide bandpass characteristics appropriate for that channel spacing.

Fig. 2 shows another representative WDM communication system 200 in which the present invention may be practiced. System 200 has N optical transmitters 202-i and N optical receivers 212-i (where i = 1, 2,... N) coupled through an NxN optical router 214. Transmitters 202 and receivers 212 are similar to transmitters 102 and receivers 112, respectively, of system 100. In one embodiment, router 214 is an optical switch fabric, e.g., an arrayed waveguide grating (AWG) designed to route optical signals based on wavelength. It can be appreciated by one skilled in the art that, for high channel density, e.g., 0.8 bit/s/Hz, router 214 may subject optical signals to narrow bandpass filtering similar to that in system 100.

Fig. 3 shows a block diagram of an optical transmitter 302 that can be used as optical transmitter 102 or 202. Transmitter 302 receives a binary data sequence, a_k, e.g., a pseudo-random bit stream (PRBS), and generates a corresponding modulated optical signal, $A(t)$, which

can then be applied to either multiplexer **104** (Fig. 1) or router **214** (Fig. 2). An encoder **320** converts sequence a_k into a corresponding encoded sequence, d_k. Encoder **320** may also introduce inter-symbol correlation (ISC) data into sequence a_k, as known in the art, to reduce error propagation at the receiver end of the WDM communication system. Based on sequence d_k, a

5   driver **322** generates a drive signal $V(t)$ applied to a Mach-Zehnder modulator (MZM) **326**. Using the drive signal, MZM **326** modulates a carrier signal (S_λ) generated by a laser **324**, thereby producing signal $A(t)$. It should be noted that encoder **320** may be excluded from transmitter **302**, when a binary transmission format is used and driver **322** is configured to operate based on a binary data sequence. In this situation, sequence a_k may be applied directly to driver **322**.

10   However, when a multilevel (i.e., using three or more levels) data transmission format is used, encoder **320** is deployed to convert binary sequence a_k into a corresponding multilevel sequence d_k.

Fig. 4 graphically illustrates operational principles of MZM **326**. More specifically, Fig. 4 shows the intensity of the output signal produced by MZM **326** as a function of drive voltage

15   applied to the MZM. MZM **326** modulates signal S_λ by splitting it into two portions, introducing a phase shift (φ_{12}) between them, and recombining the portions at the output. The value of φ_{12} is determined by the value of drive voltage (V) that can conveniently be measured in units of V_π, i.e., the drive voltage value corresponding to $\varphi_{12} = 180$ degrees. In operation, when $V = V_\pi$ (point C in Fig. 4), the two portions interfere destructively at the output of MZM **326**, which results in

20   substantially no light being output by the MZM. In contrast, when $V = 0$ or $2V_\pi$ (points B and D, respectively, in Fig. 4), the two portions interfere constructively at the output of MZM **326**, which results in maximum light intensity being transmitted through the MZM. As can further be seen in Fig. 4, drive voltage values that are not integer multiples of V_π result in intermediate light intensities. The phase (Φ) of the output signal produced by MZM **326** is also determined by the

25   value of the drive voltage. For example, the relative phase shift ($\Delta\Phi_{BD}$) between optical signals corresponding to points B and D is 180 degrees.

In prior-art modulation methods, MZM **326** is driven such that the intensity contrast between "high" and "low" states of signal $A(t)$ is at a maximum. For example, data modulation in a standard on-off keying format is achieved by using a binary sequence d_k and driving MZM **326**

30   with electrical signal $V(t)$ having two levels so as to induce transitions either between points B and C (inverting mode) or between points C and D (non-inverting mode). Similarly, for duobinary signaling, data modulation is achieved by using a duobinary sequence d_k and driving MZM **326** with electrical signal $V(t)$ having three levels so as to induce transitions between points B and D via point C. One skilled in the art can appreciate that other modulation formats may also be

35   implemented using MZM **326**.

A method of signal transmission according to one embodiment of the present invention will now be described in the context of duobinary modulation. However, one skilled in the art will readily understand that, in other embodiments, other modulation formats may similarly be employed.

5   Optical duobinary modulation is disclosed in detail, for example, in U.S. Patent No. 5,867,534, the teachings of which are incorporated herein by reference. Briefly, duobinary signaling uses three signal levels designated, for example, "+1", "0", and "−1". Furthermore, a duobinary sequence has no transitions between the "+1" and "−1" levels in successive time slots. Only transitions between (i) "0" and "+1" and (ii) "0" and "−1" levels can occur. A waveform

10   corresponding to one of the duobinary levels (i.e., a duobinary symbol) is transmitted during each signaling interval. For example, for the "0" bit, substantially no light is transmitted. The "+1" and "−1" bits are transmitted as light having +E and -E electric fields, respectively, where opposite polarities of the electric field correspond to a relative optical phase shift ($\Delta \Phi$) of 180 degrees. While an optical beam modulated in this manner is a three-level signal in terms of the electric

15   field, it is a two-level signal in terms of the optical power. Based on this property of duobinary signals, a conventional "binary" receiver is typically employed to receive duobinary signals. Since both "+1" and "−1" duobinary states correspond to light "on", a binary receiver converts optical duobinary signals into corresponding electrical binary signals by simply measuring optical power.

As already indicated above, prior-art duobinary modulation is implemented, e.g., by

20   configuring driver **322** to generate drive voltages as follows: (1) when $d_k = 0$, $V(t) = V_\pi$ (point C in Fig. 4); (2) when $d_k = -1$, $V(t) = 0$ (point B in Fig. 4); and (3) when $d_k = +1$, $V(t) = 2V_\pi$ (point D in Fig. 4). In this configuration, the intensity contrast of signal $A(t)$ is at a maximum and the relative optical phase shift between the "+1" and "−1" optical bits is about 180 degrees.

In accordance with one embodiment of the present invention, driver **322** is configured to

25   overdrive the prior-art duobinary voltages by a value of V_{OD} as indicated in Fig. 4. More specifically, driver **322** is configured to generate drive voltages as follows: (1) when $d_k = 0$, $V(t) = V_\pi$ (point C in Fig. 4); (2) when $d_k = -1$, $V(t) = - V_{OD}$ (point A in Fig. 4); and (3) when $d_k = +1$, $V(t) = 2V_\pi + V_{OD}$ (point E in Fig. 4). In this new configuration, the intensity contrast of signal $A(t)$ is no longer at a maximum and the relative optical phase shift between the "+1" and "−1" optical

30   bits is different from (i.e., greater or less than) 180 degrees. In one representative configuration, the intensity contrast of signal $A(t)$ is reduced by about 5% from the maximum contrast and/or the relative optical phase shift between the "+1" and "−1" optical bits is about 175 degrees.

Points A and E in Fig. 4 represent a "balanced" overdrive mode, i.e., when the positive and negative overdrive voltages have equal amplitudes. Alternatively, driver **322** may be

35   configured to generate drive voltages in an "imbalance" mode, for example, as follows: (1) when

$d_k = 0$, $V(t) = V_\pi$ (point C in Fig. 4); (2) when $d_k = -1$, $V(t) = - V_-$ (point A′ in Fig. 4); and (3) when $d_k = +1$, $V(t) = 2V_\pi + V_+$ (point E′ in Fig. 4). In this configuration, the positive and negative overdrive voltages (V_- and V_+) may have different amplitudes.

In another possible configuration, driver **322** may be configured to generate drive voltages such that, for one duobinary symbol, the corresponding prior-art voltage is overdriven, while for the other duobinary symbol, the corresponding prior-art voltage is used without any overdriving. For example, the following voltage combination may be used: (1) when $d_k = 0$, $V(t) = V_\pi$ (point C in Fig. 4); (2) when $d_k = -1$, $V(t) = - V_-$ (point A′ in Fig. 4); and (3) when $d_k = +1$, $V(t) = 2V_\pi$ (point D in Fig. 4). In yet another configuration, driver **322** may be configured to generate drive voltages such that, for one duobinary symbol, the corresponding prior-art voltage is overdriven, while, for the other duobinary symbol, the corresponding prior-art voltage is under-driven. One example of this configuration is as follows: (1) when $d_k = 0$, $V(t) = V_\pi$; (2) when $d_k = -1$, $V(t) = - V_-$; and (3) when $d_k = +1$, $V(t) = 1.9V_\pi$.

Although it may seem counterintuitive that a method of signal transmission employing a reduced intensity contrast compared to that employed in a prior-art method can improve transmission characteristics of a dense WDM communication system, it will be shown below that this is indeed the case. One reason for the improvement is that narrow bandpass filtering present in the WDM communication system (see, e.g., Fig. 1) induces signal distortions of the type that causes errors at the receiver primarily due to inter-symbol interference (ISI). The above-described overdriving technique produces a favorable phase relationship between the interfering symbols so as to reduce the detrimental effects of ISI. Overall performance improvement at the receiver is achieved despite some loss in the intensity contrast at the transmitter output because the improvement due to the ISI reduction is greater than the relatively small degradation caused by the loss of amplitude. Advantageously, depending on the bandpass properties of the system, the value(s) of V_{OD} or V_-/V_+ can be adjusted to attain optimum system performance.

Figs. 5A-B graphically show performance of system **100**, when the system is operated to transmit duobinary optical signals according to the prior-art method and one embodiment of the present invention, respectively. More specifically, Figs. 5A-B show eye diagrams of an optical 40-Gbit/s duobinary signal received by receiver **112-i** from transmitter **102-i,** when the transmitter is analogous to transmitter **302** shown in Fig. 3 and combined transmission characteristics of filters **108** are equivalent to those of a Gaussian bandpass filter having a 3dB bandwidth of 25 GHz. Fig. 5A is an eye diagram of the received signal, when MZM **326** of transmitter **302** is driven with a total drive voltage sweep of $2V_\pi$ between points B and D via point C as shown in Fig. 4. Similarly, Fig. 5B is an eye diagram of the received signal when MZM **326** of transmitter **302** is driven with a total drive voltage sweep of $2.8V_\pi$ ($V_{OD} = 0.4V_\pi$) between points A and E via point C

as further shown in Fig. 4. As can be seen, the eye diagram of Fig. 5A exhibits significant eye

closure due to the detrimental effects of narrow bandpass filtering in filters **108**. Compared to Fig.

5A, the eye diagram of Fig. 5B demonstrates significant eye improvement (i.e., opening)

advantageously produced by the use of the overdriving technique.

5   Fig. 6 graphically shows improvement in receiver sensitivity resulting from the use of one

embodiment of the present invention. More specifically, Fig. 6 shows receiver sensitivity

corresponding to a bit error rate (BER) of 10^{-9} as a function of drive voltage sweep applied to

MZM **326** of transmitter **302**. The dashed curve corresponds to a 40-Gbit/s duobinary signal

generated by transmitter **302** and sampled right at the transmitter output, without passing through a

10   transmission line. The solid curve corresponds to the same duobinary signal, but sampled at the

receiver end of a WDM communication system having optical bandpass filtering characteristics

analogous to those of a Gaussian bandpass filter with a 25-GHz full-width at half-maximum. As

can be seen in Fig. 6, in the absence of bandpass filtering, an increase of the drive voltage sweep

up to about $2.6V_\pi$ leaves the receiver sensitivity substantially unchanged, after which point the

15   receiver sensitivity begins to deteriorate sharply. In contrast, when bandpass filtering is present in

the system, an increase of the drive voltage sweep from $2V_\pi$ to about $2.9V_\pi$ decreases (i.e.,

improves) the value of receiver sensitivity by about 1.5 dB. The data of Fig. 6 also indicate that,

for this particular system, best results are achieved by overdriving the MZM by about 0.5 to

$1.25V_\pi$ (i.e., about 25 to 63%). Although not shown in Fig. 6, an additional improvement of about

20   0.3 dB can be achieved using the above-described imbalance mode.

While this invention has been described with reference to illustrative embodiments, this

description is not intended to be construed in a limiting sense. Various modifications of the

described embodiments, as well as other embodiments of the invention, which are apparent to

persons skilled in the art to which the invention pertains are deemed to lie within the principle and

25   scope of the invention as expressed in the following claims.

Although the steps in the following method claims, if any, are recited in a particular

sequence with corresponding labeling, unless the claim recitations otherwise imply a particular

sequence for implementing some or all of those steps, those steps are not necessarily intended to

be limited to being implemented in that particular sequence.